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Doubly and Singly Cabibbo Suppressed Charm Decays into the $K^+\pi^-\pi^+$ Final State

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Abstract

Branching ratios and upper limits at 90% confidence level for D^+ and $D_s^+ \to K^+\pi^-\pi^+$ decays collected in Fermilab photoproduction experiment E-687 are reported. The D^+ results are: $\Gamma(D^+ \to K^+\pi^-\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+) = (7.2 \pm 2.3 \pm 1.7) \times 10^{-3}$, $\Gamma(D^+ \to K^{*0}(892)\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+) < 0.0021$, and $\Gamma(D^+ \to K^+\rho^0(770))/\Gamma(D^+ \to K^-\pi^+\pi^+) < 0.067$. The D_s^+ results are: $\Gamma(D_s^+ \to K^+\pi^-\pi^+)/\Gamma(D_s^+ \to \phi(1020)\pi^+) = 0.28 \pm 0.06 \pm 0.05$, $\Gamma(D_s^+ \to K^{*0}(892)\pi^+)/\Gamma(D_s^+ \to \phi(1020)\pi^+) = 0.18 \pm 0.05 \pm 0.04$, and $\Gamma(D_s^+ \to K^+\rho^0(770))/\Gamma(D_s^+ \to \phi(1020)\pi^+) < 0.08$.

1 Introduction

Branching ratios and upper limits for D^+ and D_s^+ decays into the $K^+\pi^-\pi^+$ final state[10] are reported. The $D^+ \rightarrow K^+\pi^-\pi^+$ decay is doubly Cabibbo suppressed while the $D_s^+ \rightarrow K^+\pi^-\pi^+$ decay is singly Cabibbo suppressed. The data were collected from 500 million events recorded in photoproduction experiment E-687 conducted in the Fermilab Wideband Photon beam during the 1990-1991 fixed target run.

The E-687 detector [1] is a large aperture, multiparticle, magnetic spectrometer with excellent vertex measurement, particle identification, and calorimetric capabilities. The experiment used a high energy bremsstrahlung photon beam and beryllium target. The average tagged photon momentum was 220 GeV/c. Charged particles coming from the beryllium target were tracked by 12 planes of silicon microstrips providing high resolution tracking in the vertex region. The mean primary and secondary vertex separation resolution for the decays discussed in this analysis is 540μm. Following the microstrip system, charged particles passed through two analysis magnets interleaved with 5 stations of multiwire proportional chambers (PWC's). Three multicell threshold Čerenkov counters allowed kaon-pion identification over the momentum range from 4.5 to 61.5 GeV/c. The experimental trigger required the presence of at least two charged tracks in the spectrometer, their trajectories outside the Bethe-Heitler pair region, and more than 40 GeV of energy detected in the hadronic calorimeter.

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[10] Unless otherwise specified, the charge conjugate state is implied for all decays presented.

Fig. 1. Invariant mass distributions for $K^+\pi^-\pi^+$ and $K^-\pi^+\pi^+$ using cuts optimized for the D^+ analysis. The D^+ yields are 20.9 ± 6.6 and 2903 ± 62 events respectively.

2 $D^+ \to K^+\pi^-\pi^+$ Analysis

The final event sample was determined using the particle identification and topology discrimination capabilities of the E-687 spectrometer. The kaon was required to be identified by the Čerenkov system as consistent with the kaon hypothesis or the kaon/proton hypothesis. [11] The pions were required to be identified as inconsistent with the electron and heavy particle hypotheses. After three PWC tracks satisfying the appropriate Čerenkov identifications were found, the decay topology was reconstructed.

To reconstruct a D^+ candidate, the three microstrip tracks uniquely linked to the PWC tracks, were used to reconstruct the charm production and decay vertices. E-687 has developed a candidate driven vertexing algorithm to study systematically the decay topology[1]. The various routines calculate confidence levels for candidate vertices and their relative separation and isolation from other tracks and vertices. For the analyses reported here the quantities used to discriminate against backgrounds were: the confidence levels of the primary and secondary vertices, PCL and DCL respectively; the vertex confidence level for adding a track already in the secondary vertex to the primary vertex, ISO1; the vertex confidence level for including tracks not already assigned to the primary or secondary vertices into the secondary vertex, ISO2; the spatial separation of the primary and secondary vertices in units of its error, ℓ/σ_ℓ; and the separation of the secondary vertex from the downstream end of the target in units of its error, ℓ_v/σ_v.

The final sample used to measure the $K^+\pi^-\pi^+$ branching ratio relative to $K^-\pi^+\pi^+$ was determined by optimizing the quantity $\mathcal{S}/\sqrt{B}$ in the space of appropriate cuts. The quantity $\mathcal{S}$ is the $K^-\pi^+\pi^+$ signal yield while B is the background below the signal. Figure 1 shows the $K^+\pi^-\pi^+$ and $K^-\pi^+\pi^+$ invariant mass distributions for the optimized cuts: $\ell/\sigma_\ell > 15$, PCL $> 1\%$, DCL $> 1\%$, ISO1 $< 0.1\%$, ISO2 $< 0.01\%$, and $\ell_v/\sigma_v > 1.5$. The $K^+\pi^-\pi^+$ invariant mass distribution was fit with two Gaussian peaks added to a polynomial background. The D^+ mass and width were constrained to the $K^-\pi^+\pi^+$ val-

[11] By kaon/proton hypothesis it is meant that the Čerenkov response could have been produced by either a kaon or proton.

Fig. 2. Stability of the ratios $\Gamma(D^+ \rightarrow K^+\pi^-\pi^+)/\Gamma(D^+ \rightarrow K^-\pi^+\pi^+)$ and $\Gamma(D_s^+ \rightarrow K^+\pi^-\pi^+)/\Gamma(D_s^+ \rightarrow \phi(1020)\pi^+)$ as ℓ/σ_ℓ is varied.

ues. The D_s^+ mass and width were constrained to the values determined by Monte Carlo. The $K^-\pi^+\pi^+$ invariant mass distribution was fit using a single unconstrained Gaussian added to a polynomial. The D^+ yields are 20.9 ± 6.6 $K^+\pi^-\pi^+$ events and 2903 ± 62 $K^-\pi^+\pi^+$ events. Monte Carlo studies indicate efficiencies for the two states are nearly identical and therefore cancel in a relative branching ratio calculation. The resulting branching ratio is

$$\frac{\Gamma(D^+ \rightarrow K^+\pi^-\pi^+)}{\Gamma(D^+ \rightarrow K^-\pi^+\pi^+)} = 0.0072 \pm 0.0023 \pm 0.0017. \tag{1}$$

The first error bar is statistical while the second reflects the systematic uncertainty associated with the background shape used in the fit, the uncertainty in the efficiency calculation due to the possibility of intermediate two-body resonant decay modes leading to the $K^+\pi^-\pi^+$ final state, and the uncertainty arising from possible contributions to the signal from known charm backgrounds. To check for the possibility of contamination from charm backgrounds, numerous direct searches for known reflections, such as $D_s^+ \rightarrow K^+K^-\pi^+$ and $\Lambda_c^+ \rightarrow pK^-\pi^+$, were performed. Additionally, contributions to the $K^+\pi^-\pi^+$ invariant mass distribution were investigated using a general photoproduction Monte Carlo [12] where all charm species and known decay modes are simulated for both the charm and anticharm particle. No significant contribution in the D^+ mass region was observed from the charm reflection searches and hence no correction was made to the $D^+ \rightarrow K^+\pi^-\pi^+$ yield. The $\ell/\sigma_\ell > 15$ requirement helps to eliminate contamination from these charm particles, all of which are shorter lived than the D^+. The top plot in Figure 2 shows the variation of the branching ratio as the ℓ/σ_ℓ cut is varied. The stability of the branching ratio is a further check that the contamination from other charm sources is not statistically significant.

[12] The Monte Carlo program consisted of simulation algorithms for the E-687 apparatus[1] and the Lund group event generator packages PYTHIA 5.6 and JETSET 7.3[2].

Fig. 3. Invariant mass distributions for $K^+\rho^0(770)$, and $K^{*0}(892)\pi^+$ events. D^+ yields from fits are 5.8 ± 5.3 and 0 ± 1 events respectively.

3 Searches for $D^+ \to K^+\rho^0(770)$ and $K^{*0}(892)\pi^+$

The $K^+\pi^-\pi^+$ three-body final state may include contributions from intermediate two-body resonant decay modes. Those expected to dominate are $K^+\rho^0(770)$ and $K^{*0}(892)\pi^+$. Searches for both these decay modes were performed using the same set of cuts described in the inclusive analysis. The left plot in Figure 3 shows the $K^+\pi^-\pi^+$ mass distributions for events satisfying the above cuts and requiring the $\pi^+\pi^-$ invariant mass to be within $\pm 1\Gamma$ of the accepted $\rho^0(770)$ mass[3], where Γ is the accepted $\rho^0(770)$ natural width[3]. To correct for other resonant or non-resonant $K^+\pi^-\pi^+$ decays, $K^+\pi^-\pi^+$ candidates having a $\pi^+\pi^-$ invariant mass falling in 1Γ wide mass windows centered $\pm 2.5\Gamma$ from the accepted $\rho^0(770)$ mass were subtracted. Since a significant portion of the D^+ signal resides in the long Breit-Wigner tails of the resonance, a Monte Carlo sample was used to correct for D^+ events falling outside the 1Γ mass cut and and also to account for the D^+ events subtracted from the high and low mass windows. The right plot in Figure 3 shows the $K^+\pi^-\pi^+$ invariant mass distribution [13] where the $K^+\pi^-$ invariant mass was required to be within $\pm 1\Gamma$ of the accepted $K^{*0}(892)$ mass[3], and again Γ is the accepted $K^{*0}(892)$ natural width[3]. The invariant mass distributions were fit with single Gaussian peaks added to a polynomial background. The Gaussian means and widths were constrained to values determined from Monte Carlo studies. The D^+ yields are 5.8 ± 5.3 $K^+\rho^0(770)$ events and 0 ± 1 $K^{*0}(892)\pi^+$ events.

To calculate branching ratio upper limits for these decay modes, an integrated likelihood method was employed. The fit likelihood function is integrated with respect to all fit parameters and the 90% confidence level upper limit on the signal parameter $\mathcal{S}$ is determined by the condition

$$\frac{\int^{\mathcal{S}_{0.9}} d\mathcal{S} \int_{\Omega_{\vec{p}}} \prod_i dp_i \mathcal{L}(\vec{p})}{\int_{\Omega_{\mathcal{S}}} d\mathcal{S} \int_{\Omega_{\vec{p}}} \prod_i dp_i \mathcal{L}(\vec{p})} = 0.9 \qquad (2)$$

where $\vec{p}$ is the vector of fit parameters (excluding $\mathcal{S}$) and $\Omega_{\mathcal{S}}$ and $\Omega_{\vec{p}}$ are

[13] Due to the lack of statistics, events were not subtracted from this invariant mass distribution.

Fig. 4. Invariant mass distributions for $K^+\pi^-\pi^+$, and $\phi(1020)\pi^+$ events using cuts optimized for the D_s^+ analysis. The D_s^+ yields are 85.5 ± 16.0 and 200.5 ± 15.8 events respectively.

the domains of $\mathcal{S}$ and $\vec{p}$. Using this method, the 90% confidence level upper limits on the number of $D^+ \to K^+\rho^0(770)$ and $K^{*0}(892)\pi^+$ events were found to be 14.4, and 2.8 respectively. The resulting upper limits are, $\Gamma(D^+ \to K^+\rho^0(770))/\Gamma(D^+ \to K^-\pi^+\pi^+) < 0.0067$, and $\Gamma(D^+ \to K^{*0}(892)\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+) < 0.0021$, where the appropriate resonance decay branching ratios have been accounted for.

4 $D_s^+ \to K^+\pi^-\pi^+$ Analysis.

Since the lifetime of the D_s^+ is shorter than that of the D^+, it is necessary to apply an alternative set of cuts to obtain comparable rejections against backgrounds when searching for a $D_s^+ \to K^+\pi^-\pi^+$ signal. For example, the necessity of relaxing the decay length cut (ℓ/σ_ℓ) can be partially compensated for by requiring the magnitude of the $K^+\pi^-\pi^+$ three–momentum to be greater than some minimum value. This has been shown to preferentially remove background sources while being efficient for $D_s^+ \to K^+\pi^-\pi^+$ events. Figure 4 shows the $K^+\pi^-\pi^+$ invariant mass distribution for $\ell/\sigma_\ell > 10$, $P_{\rm D} > 70$ GeV/c, PCL $> 1\%$, DCL $> 5\%$, ISO1 $< 1\%$, and ISO2 $< 1\%$, where $P_{\rm D}$ is the magnitude of the $K^+\pi^-\pi^+$ three- momentum. The kaon was required to be identified by the Čerenkov system as consistent with either the kaon or kaon/proton hypotheses, while the pion was identified as being inconsistent with an electron and heavy particle. The distribution was fit using two Gaussian peaks added to a polynomial background. Unlike the D^+ analysis, the Gaussian means and widths were allowed to vary during the fit and were found to be consistent within errors with the values obtained from Monte Carlo studies. The D_s^+ yield is 85.5 ± 16.0 events.

The decay mode used for normalization of the branching ratio is $D_s^+ \to \phi(1020)\pi^+$. Since the $\phi(1020)$ resonance is very narrow, only the K^+ from $\phi(1020)\pi^+$ decays was required to be identified by the Čerenkov system as consistent with the kaon or kaon/proton hypotheses. The pion identification was the same as the $K^+\pi^-\pi^+$ requirement. Figure 4 shows the $K^+K^-\pi^+$ invariant mass distribution where the K^+K^- mass was constrained to be within

7.5 MeV/c^2 of the accepted $\phi(1020)$ mass[3]. All other cuts were the same as those used for the $K^+\pi^-\pi^+$ signal, with the exception of the ISO1 cut. The ISO1 cut was relaxed to be less than 50% since it becomes less efficient for decay modes with lower Q values. Monte Carlo studies have verified that no systematic bias is introduced into the branching ratio measurements presented below and further these results are stable over a large range of ISO1 values. To correct for contributions from other intermediate two-body resonant decay modes leading to the $K^-K^+\pi^+$ decays, events with a K^+K^- invariant mass falling outside the $\phi(1020)$ resonance were subtracted in a manner analogous to that described in $D^+ \to K^+\rho^0(770)$ analysis. The invariant mass distribution was fit using two Gaussian peaks added to a polynomial background. The resulting yield in the D_s^+ peak is 200.5 ± 15.8 events. After correcting for detector acceptance and efficiency, the measured inclusive $D_s^+ \to K^+\pi^-\pi^+$ branching ratio is

$$\frac{\Gamma(D_s^+ \to K^+\pi^-\pi^+)}{\Gamma(D_s^+ \to \phi(1020)\pi^+)} = 0.28 \pm 0.06 \pm 0.05. \tag{3}$$

The first error bar is statistical while the second is systematic. The systematic uncertainties shown to affect the measurement are those associated with the background shape used in the fit, contamination from charm reflections, the D_s^+ momentum distribution, and uncertainty in the efficiency calculation due to the possibility of intermediate two-body resonant decay modes leading to the $K^+\pi^-\pi^+$ final state. The bottom plot in Figure 2 shows the branching ratio as the ℓ/σ_ℓ cut is varied. The stability of the branching ratio demonstrates good agreement between the data and the Monte Carlo simulation of these decays.

The $\Gamma(D_s^+ \to K^+\pi^-\pi^+)/\Gamma(D_s^+ \to \phi(1020)\pi^+)$ result may be combined with the results from our Dalitz plot analysis of $D_s^+ \to K^+K^-\pi^+$[4] to yield $\Gamma(D_s^+ \to K^+\pi^-\pi^+)/\Gamma(D_s^+ \to K^+K^-\pi^+) = 0.23 \pm 0.07$ where the $K^+K^-\pi^+$ interference effects have been neglected due to the small statistical significance of the measurement. Previously, an indirect measurement of $\Gamma(D_s^+ \to K^+\pi^-\pi^+)$ was made by the NA-32 collaboration[5]. No signal was observed, but the partial width was inferred using topological normalization and determined to be $\Gamma(D_s^+ \to K^+\pi^-\pi^+) = 0.003^{+0.004}_{-0.003}$. Using the accepted partial width, $\Gamma(D_s^+ \to \phi(1020)\pi^+) = 0.035 \pm 0.004$[3], and the branching ratio presented above, the partial width from the present analysis is $\Gamma(D_s^+ \to K^+\pi^-\pi^+) = 0.0098 \pm 0.0029$.

Fig. 5. Invariant mass distributions for $K^+\rho^0(770)$ and $K^{*0}(892)\pi^+$ events. D_s^+ yields are 5.0 ± 9.8 and 24.7 ± 6.8 events respectively.

5 Searches for $D_s^+ \to K^+\rho^0(770)$ and $K^{*0}(892)\pi^+$.

As was the case for the D^+, searches for the decays $D_s^+ \to K^+\rho^0(770)$ and $K^{*0}(892)\pi^+$ were performed. The topology and particle identification cuts used for these analyses were identical to those used in the D_s^+ inclusive analysis. Mass cuts on the resonances, $\rho^0(770)$ and $K^{*0}(892)$, are also identical to those used for the D^+ work. Figure 5 shows the $K^+\pi^-\pi^+$ invariant mass distributions for candidate $K^+\rho^0(770)$ and $K^{*0}(892)\pi^+$ decays where $K^+\pi^-\pi^+$ events were subtracted as described in the $D^+ \to K^+\rho^0(770)$ analysis to account for other possible resonant or non-resonant contributions. Monte Carlo corrections were also applied to correct for the D_s^+ signal in the resonance tails and the resulting reduction of D_s^+ signal during the subtraction process.

Fits to the invariant mass distributions used single Gaussian peaks and added to a polynomial background, where the Gaussian means and widths were fixed to the values determined in Monte Carlo studies. The fits yield 5.0 ± 9.8 $K^+\rho^0(770)$ events and 24.7 ± 6.8 $K^{*0}(892)\pi^+$ events. Figure 6 shows the $\pi^+\pi^-$ and $K^+\pi^-$ invariant mass distributions for events with a $K^+\pi^-\pi^+$ mass within ± 2 standard deviations of the accepted D_s^+ mass where $\sigma = 12.4$ MeV/c^2. To account for other sources of $K^{*0}(892)$ and $\rho^0(770)$, $K^+\pi^-$ and $\pi^+\pi^-$ candidates formed from $K^+\pi^-\pi^+$ combinations falling in 2σ wide mass windows centered $\pm 5\sigma$ from the accepted D_s^+ mass were subtracted. The two-body invariant mass distributions were fit using a relativistic p-wave Breit-Wigner convoluted with a Gaussian peak added to a polynomial background. The Gaussian function accounts for the finite resolution of the E-687 spectrometer. The resulting $K^+\pi^-$ and $\pi^+\pi^-$ signal yields were found to be consistent within errors with the yields from the $K^{*0}(892)\pi^+$ and $K^+\rho^0(770)$ invariant mass distribution fits. Using the likelihood upper limit technique described above at 90% confidence level the number of $K^+\rho^0(770)$ decays is less than 18.9, which corresponds to a branching ratio upper limit relative to $D_s^+ \to \phi(1020)\pi^+$ of

$$\frac{\Gamma(D_s^+ \to K^+\rho^0(770))}{\Gamma(D_s^+ \to \phi(1020)\pi^+)} < 0.08. \tag{4}$$

The $D_s^+ \to K^{*0}(892)\pi^+$ branching ratio relative to $D_s^+ \to \phi(1020)\pi^+$ is mea-

Fig. 6. $K^+\pi^-$ and $\pi^+\pi^-$ invariant mass distributions for $K^+\pi^-\pi^+$ candidates within 2.5 standard deviations ($\sigma = 12.4$ MeV/c^2) of the accepted D_s^+ mass.

sured to be

$$\frac{\Gamma(D_s^+ \to K^{*0}(892)\pi^+)}{\Gamma(D_s^+ \to \phi(1020)\pi^+)} = 0.18 \pm 0.05 \pm 0.04. \quad (5)$$

6 Summary

Results of searches for doubly Cabibbo suppressed D^+ decays and singly Cabibbo suppressed D_s^+ decays using the $K^+\pi^-\pi^+$ final state have been reported. Evidence for the decay mode $D^+ \to K^+\pi^-\pi^+$ is observed and the branching ratio relative to $D^+ \to K^-\pi^+\pi^+$ has been presented. There have been previous mesurements consistent with doubly Cabibbo suppressed decays[6]. Preliminary results for this decay mode have also been reported by Fermilab experiment E-791[7]. The inclusive ratio presented is $\Gamma(D^+ \to K^+\pi^-\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+) = (7.2 \pm 2.3 \pm 1.7) \times 10^{-3}$. The previously published upper limit of 5% was reported in reference [8]. Also presented were branching ratio upper limits, at 90% confidence level, for the intermediate two-body resonant decay modes $D^+ \to K^{*0}(892)\pi^+$ and $D^+ \to K^+\rho^0(770)$ relative to $D^+ \to K^-\pi^+\pi^+$. The limits are $\Gamma(D^+ \to K^+\rho^0(770))/\Gamma(D^+ \to K^-\pi^+\pi^+) < 0.0067$ and $\Gamma(D^+ \to K^{*0}(892)\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+) < 0.0021$.

Also included in this work is evidence for the decay mode $D_s^+ \to K^+\pi^-\pi^+$ and the first measurement of the branching ratio $\Gamma(D_s^+ \to K^+\pi^-\pi^+)/\Gamma(D_s^+ \to \phi(1020)\pi^+)$. The inclusive branching ratio is measured to be $0.28 \pm 0.06 \pm 0.05$. Evidence for the intermediate two-body resonant decay $D_s^+ \to K^{*0}(892)\pi^+$ is observed and the branching ratio $\Gamma(D_s^+ \to K^{*0}(892)\pi^+)/\Gamma(D_s^+ \to \phi(1020)\pi^+) = 0.18 \pm 0.05 \pm 0.04$ was presented. Finally, no signal was observed in the decay $D_s^+ \to K^+\rho^0(770)$ and the upper limit at 90% confidence level $\Gamma(D_s^+ \to K^+\rho^0(770))/\Gamma(D_s^+ \to \phi(1020)\pi^+) < 0.08$ was determined.

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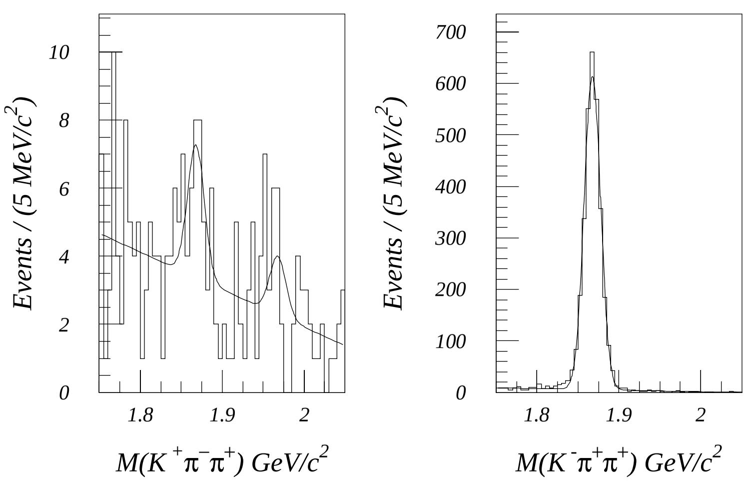
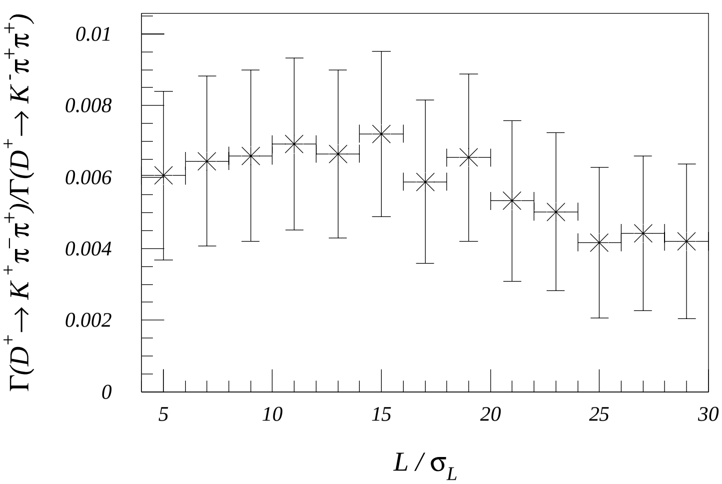
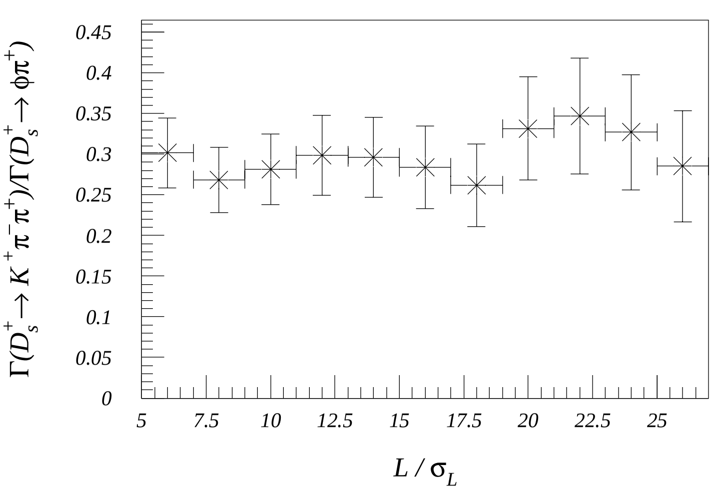
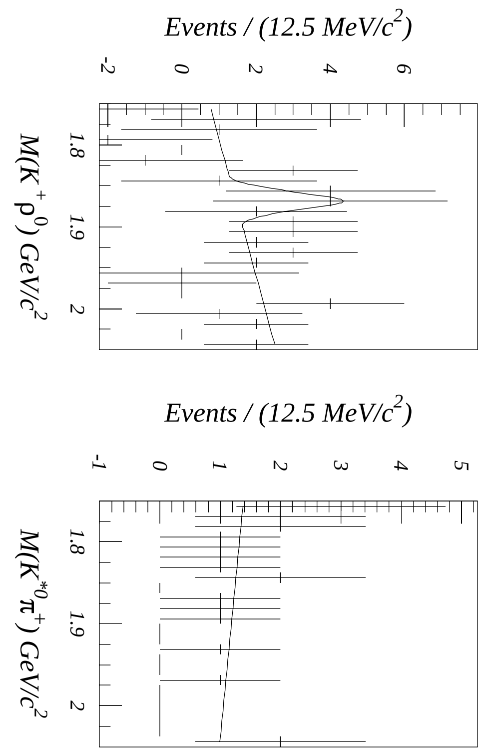

Events / (5 MeV/c2)
0
2
4
6
8
10
1.8
1.9
2
M(K+π−π+) GeV/c2
Events / (5 MeV/c2)
0
100
200
300
400
500
600
700
1.8
1.9
2
M(K-π+π+) GeV/c2



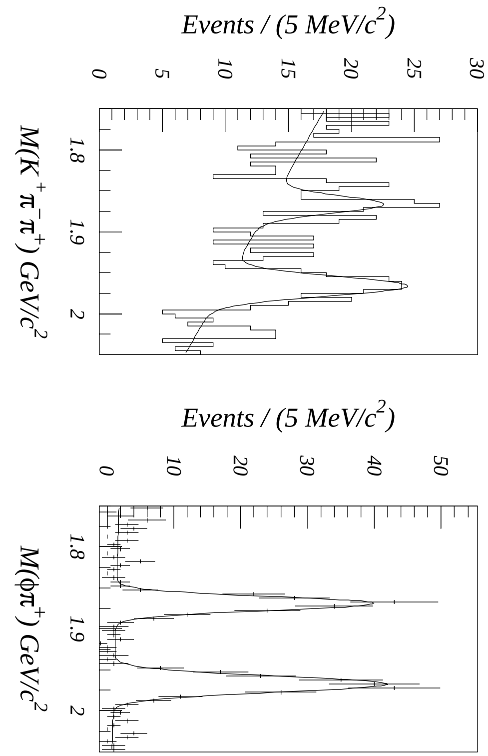
$\Gamma(D^+ \to K^+\pi^-\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+)$
0
0.002
0.004
0.006
0.008
0.01
5
10
15
20
25
30
L / σ_L



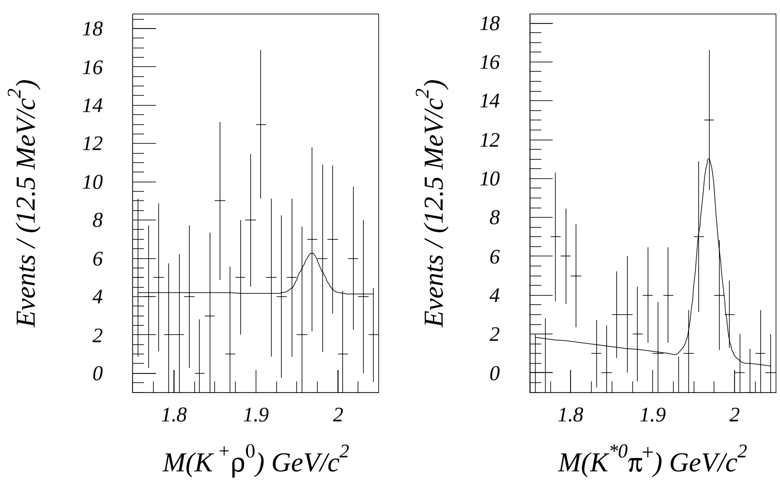
$\Gamma(D_s^+ \to K^+\pi^-\pi^+)/\Gamma(D_s^+ \to \phi\pi^+)$
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
5
7.5
10
12.5
15
17.5
20
22.5
25
L / σ_L



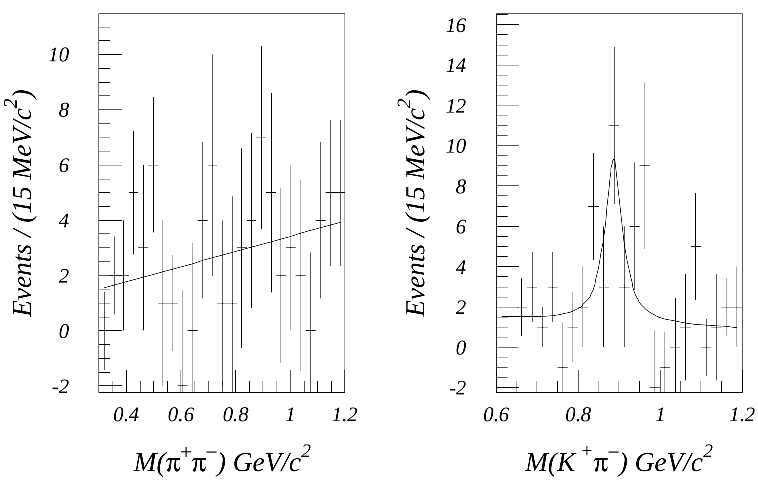
Events / (12.5 MeV/c2)
-2 0 2 4 6
M(K+ρ0) GeV/c2
1.8 1.9 2
Events / (12.5 MeV/c2)
-1 0 1 2 3 4 5
M(K*0π+) GeV/c2
1.8 1.9 2



Events / (5 MeV/c2)
0
5
10
15
20
25
30
1.8
1.9
2
M(K+π−π+) GeV/c2
Events / (5 MeV/c2)
0
10
20
30
40
50
1.8
1.9
2
M(φπ+) GeV/c2



Events / (12.5 MeV/c2)
0
2
4
6
8
10
12
14
16
18
1.8
1.9
2
M(K+ρ0) GeV/c2
Events / (12.5 MeV/c2)
0
2
4
6
8
10
12
14
16
18
1.8
1.9
2
M(K*0π+) GeV/c2



Events / (15 MeV/c^2)
-2
0
2
4
6
8
10
0.4
0.6
0.8
1
1.2
M($\pi^+\pi^-$) GeV/c^2
Events / (15 MeV/c^2)
-2
0
2
4
6
8
10
12
14
16
0.6
0.8
1
1.2
M($K^+\pi^-$) GeV/c^2